3/8

(12) UK Patent Application (19) GB (11) 2 231 958 (13) A

(43) Date of A publication 28.11.1990

(21) Application No 9007810.6

(22) Date of filing 06.04.1990

(30) Priority data
(31) 01089478 (32) 07.04.1989 (33) JP
01089479
01089480

(51) INT CL⁵
G01N 21/64

(52) UK CL (Edition K)
G1A AA4 AA6 ACD ACJ AC1 AC10 AC9 AD1 AD3 AD4 AD6 AG1 AG17 AG4 AG7 AP1 AP17 AP6 AP9 AR7 AS10 AS12 AS4 AS5 AT14 AT15 AT23 AT3 AT8
U1S S1594 S2088

(56) Documents cited
GB 2178623 A GB 2177195 A GB 2172991 A
GB 2133875 A GB 1139704 A EP 0284660 A1
EP 0141382 A2

(58) Field of search
UK CL (Edition K) G1A ACD ACJ
INT CL⁵ G01N 21/64
Online database: WPI

(71) Applicant
Hamamatsu Photonics Kabushiki Kaisha

(Incorporated in Japan)

1126-1 Ichino-cho, Hamamatsu-shi, Shizuoka-ken, Japan

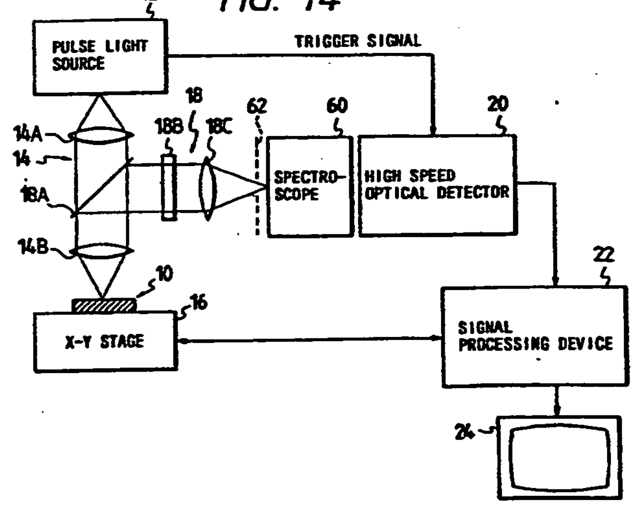
(72) Inventors
Musubu Koishi
Motoyuki Watanabe
Yoshihiko Mizushima
Hirofumi Kan

(74) Agent and/or Address for Service
Gill Jennings & Every
53-64 Chancery Lane, London WC2A 1HN,
United Kingdom

(54) Measuring fluorescence characteristics

(57) A fluorescent characteristic inspecting apparatus comprises a light source 12 for exciting a specimen via an optical system 14; a device 16 for moving the measurement position of the specimen; an optical system 18 applying photoluminescence from the specimen to a high speed optical detector 20 for detecting data on a time intensity waveform of the photoluminescence in synchronization with the operation of the light source; and a signal processing device 22 for analyzing the data on the time intensity waveform at a plurality of measurement points to obtain the spatial intensity distribution and lifetime distribution of the photoluminescence or the correlation distribution of both. A spectroscope 60 may be placed in front of a 2-D streak camera 20 which is triggered by a signal from a photodiode viewing a pulsed light source 12. A CCD camera viewing a fluorescent screen on the streak camera obtains the time and wavelength distribution of fluorescence from each point of the specimen.

FIG. 14



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

GB 2 231 958 A

FIG. 1

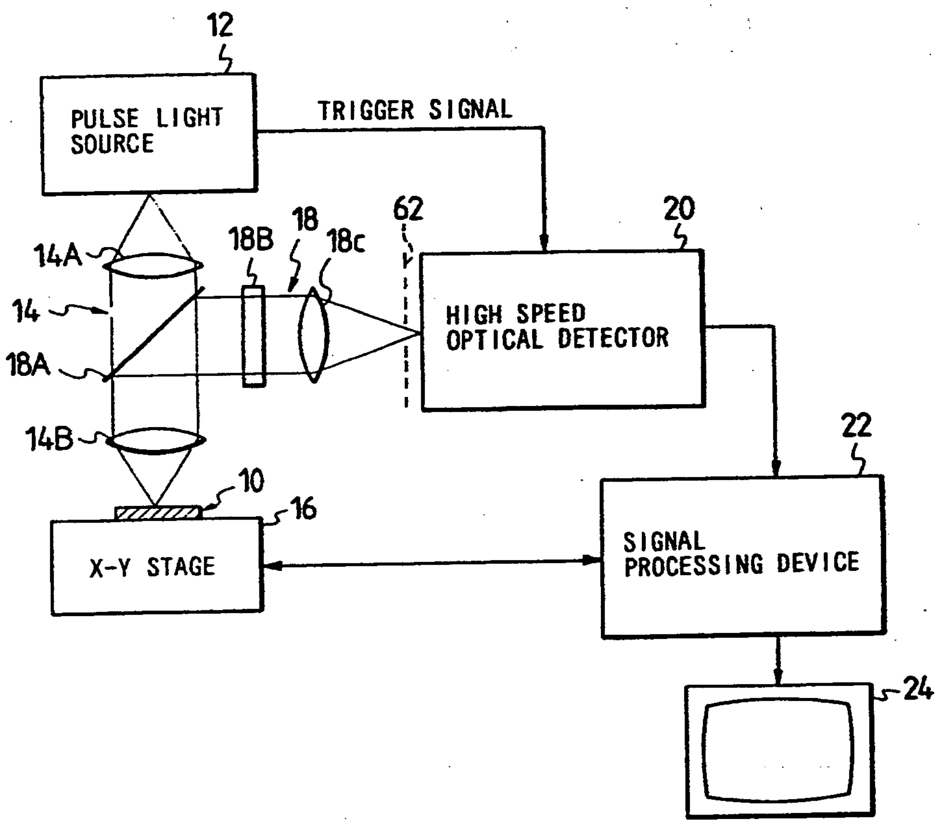

12
PULSE LIGHT SOURCE
TRIGGER SIGNAL
14A
14
18A
14B
18B
18
18c
62
20
HIGH SPEED OPTICAL DETECTOR
10
16
X-Y STAGE
22
SIGNAL PROCESSING DEVICE
24

FIG. 2

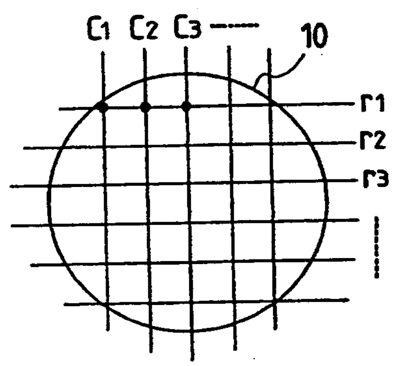

C1 C2 C3
10
r1
r2
r3

FIG. 3

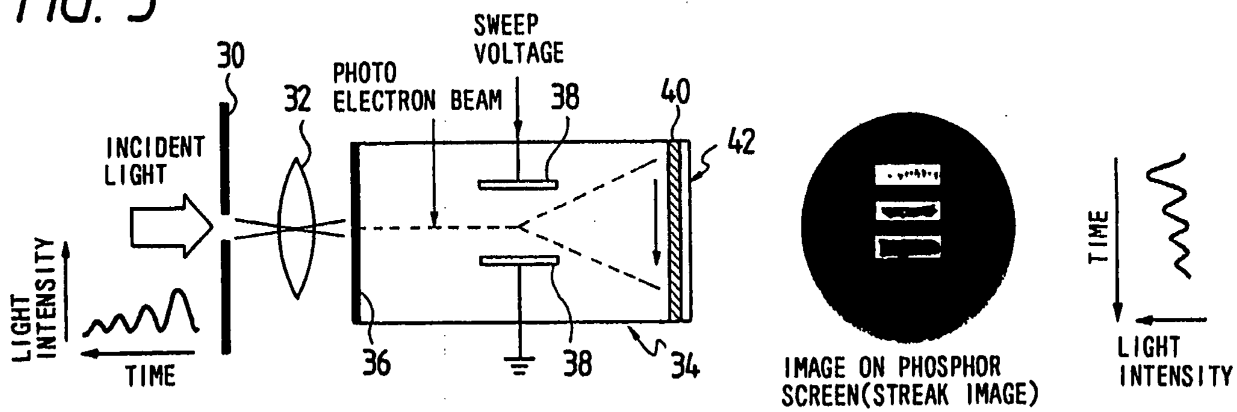

30
32
PHOTO
ELECTRON BEAM
SWEEP
VOLTAGE
38
40
42
INCIDENT
LIGHT
LIGHT
INTENSITY
TIME
36
38
34
IMAGE ON PHOSPHOR
SCREEN(STREAK IMAGE)
TIME
LIGHT
INTENSITY

FIG. 4

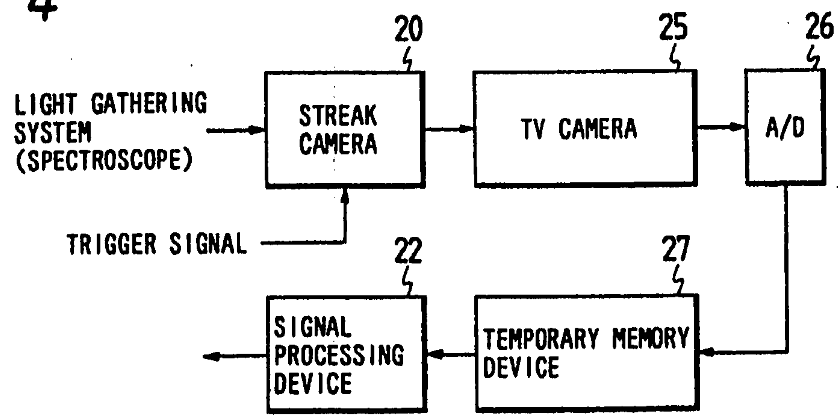

20
25
26
LIGHT GATHERING
SYSTEM
(SPECTROSCOPE)
STREAK
CAMERA
TV CAMERA
A/D
TRIGGER SIGNAL
22
27
SIGNAL
PROCESSING
DEVICE
TEMPORARY MEMORY
DEVICE

FIG. 5

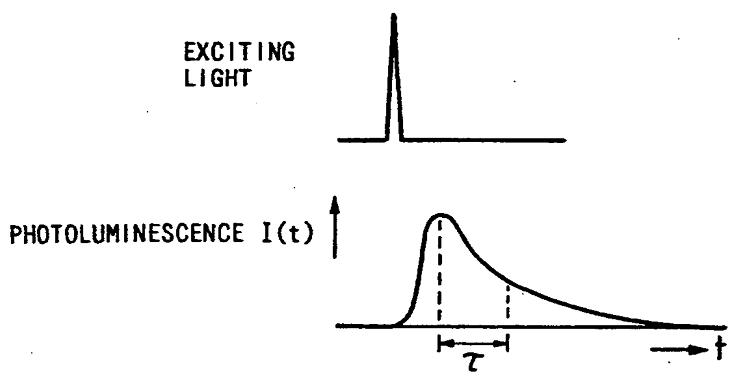

EXCITING
LIGHT
PHOTOLUMINESCENCE I(t)
τ
t

FIG. 7

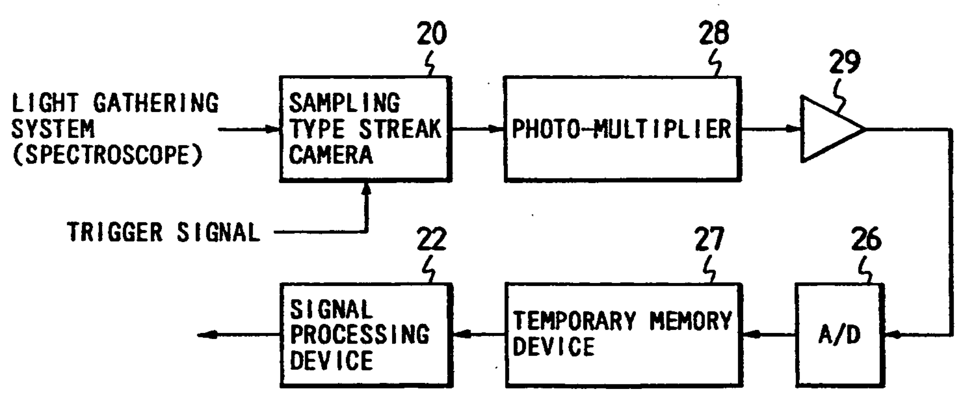

20
28
29
LIGHT GATHERING
SYSTEM
(SPECTROSCOPE)
SAMPLING
TYPE STREAK
CAMERA
PHOTO-MULTIPLIER
TRIGGER SIGNAL
22
27
26
SIGNAL
PROCESSING
DEVICE
TEMPORARY MEMORY
DEVICE
A/D

FIG. 6

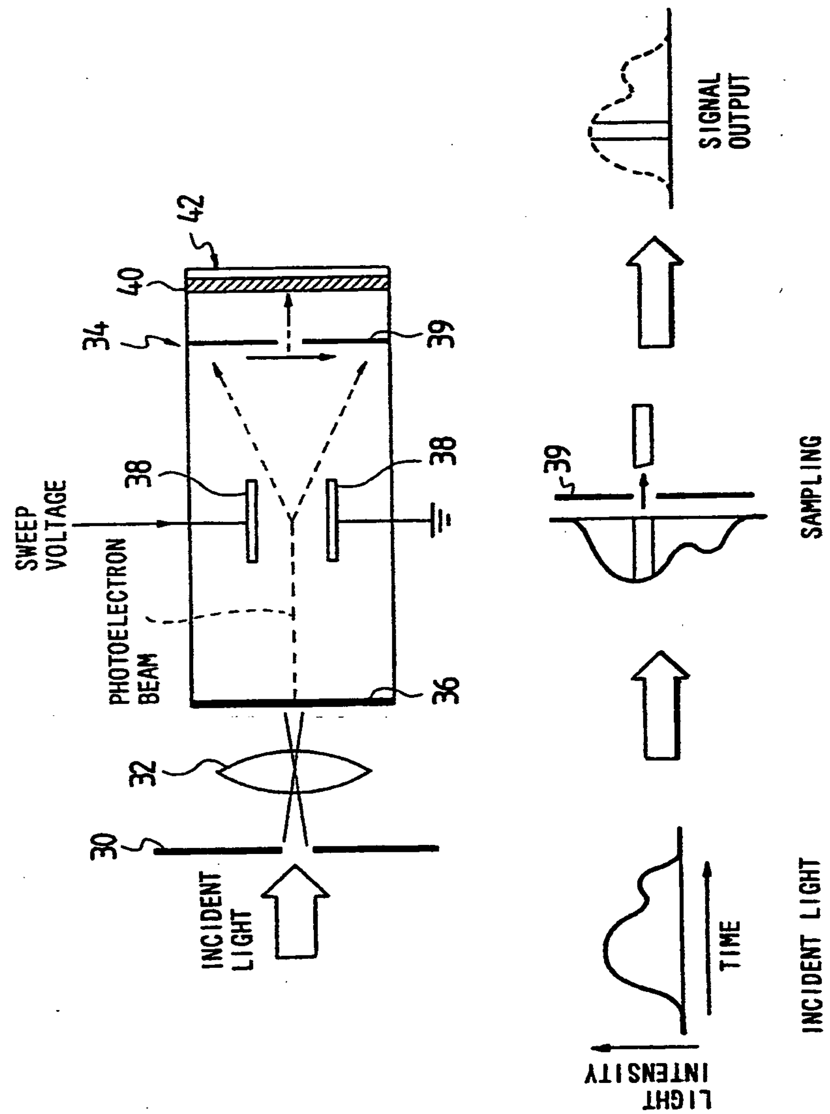

INCIDENT LIGHT
30
32
36
PHOTOELECTRON BEAM
SWEEP VOLTAGE
38
38
34
39
40
42
LIGHT INTENSITY
TIME
INCIDENT LIGHT
39
SAMPLING
SIGNAL OUTPUT

FIG. 8

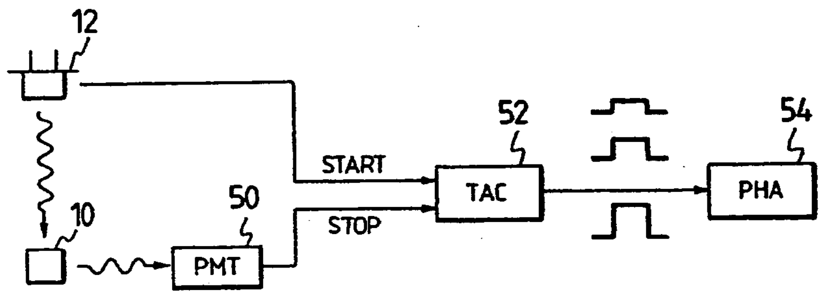


FIG. 9

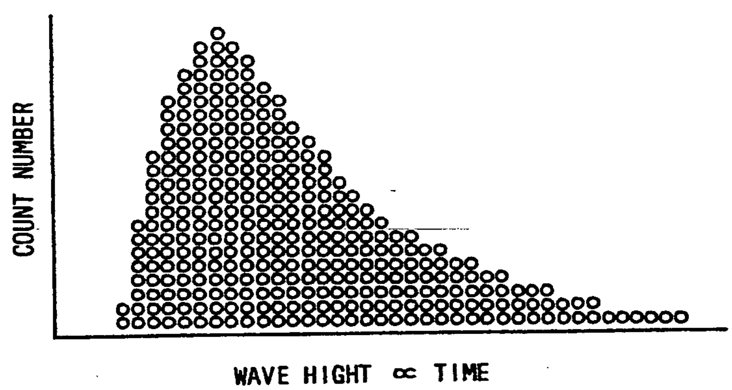


FIG. 10

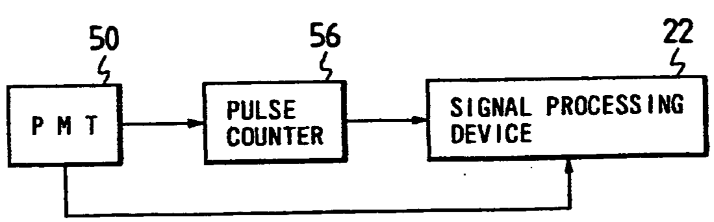


FIG. 11

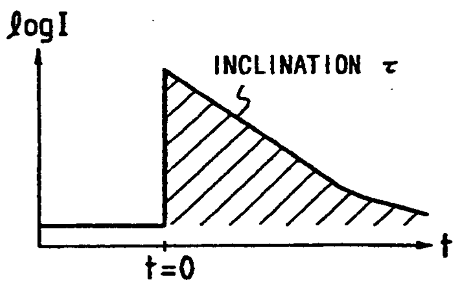


FIG. 12

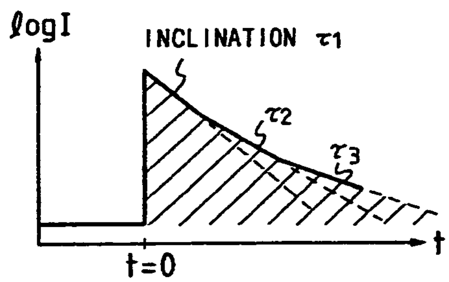


FIG. 13

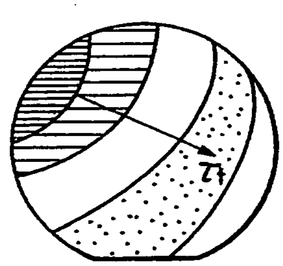


FIG. 14

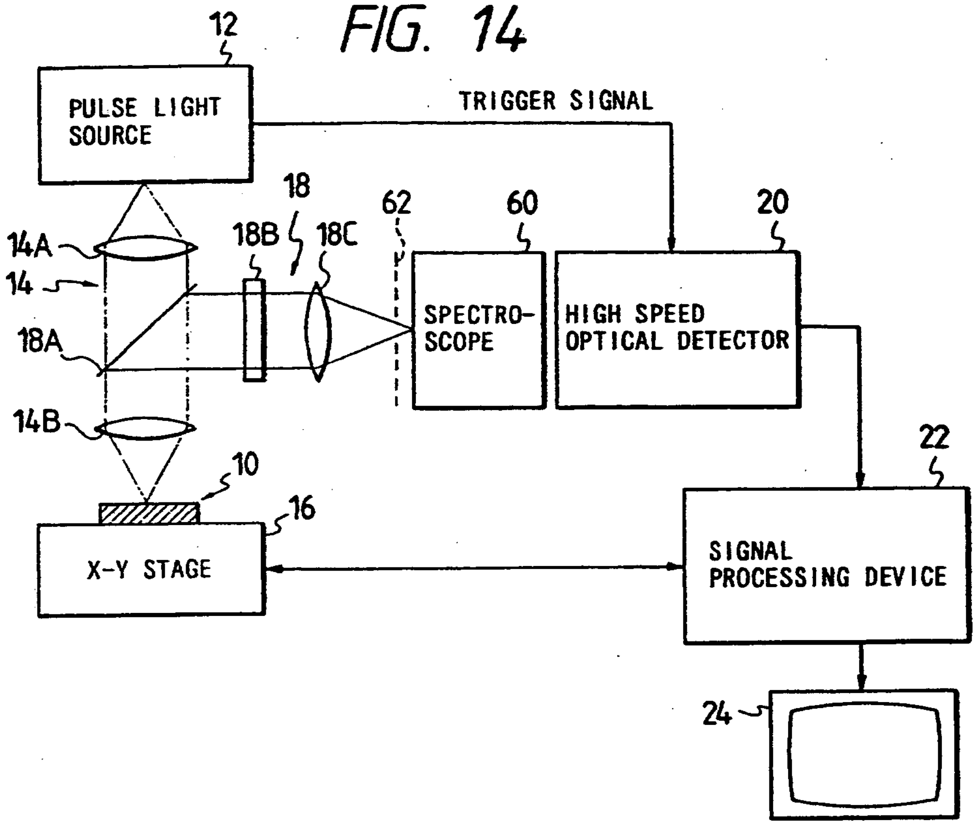

12
PULSE LIGHT SOURCE
TRIGGER SIGNAL
18
62
60
20
14A
14
18B
18C
SPECTRO-SCOPE
HIGH SPEED OPTICAL DETECTOR
18A
14B
22
10
16
X-Y STAGE
SIGNAL PROCESSING DEVICE
24

FIG. 15

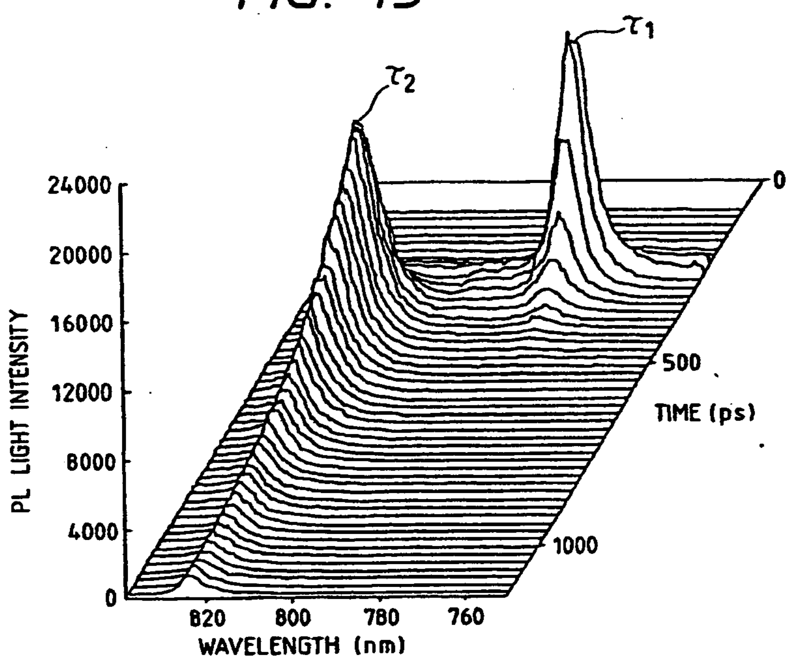

τ1
τ2
24000
20000
16000
12000
8000
4000
0
PL LIGHT INTENSITY
0
500
TIME (ps)
1000
820
800
780
760
WAVELENGTH (nm)

FIG. 16

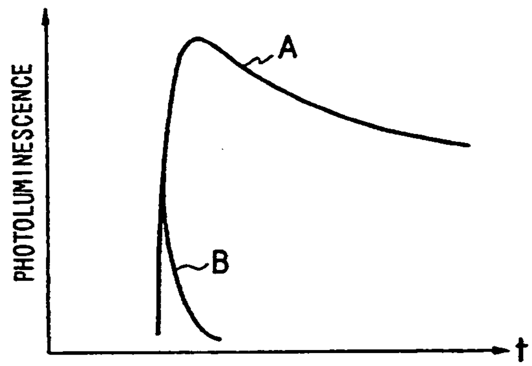

PHOTOLUMINESCENCE
A
B
t

FIG. 17

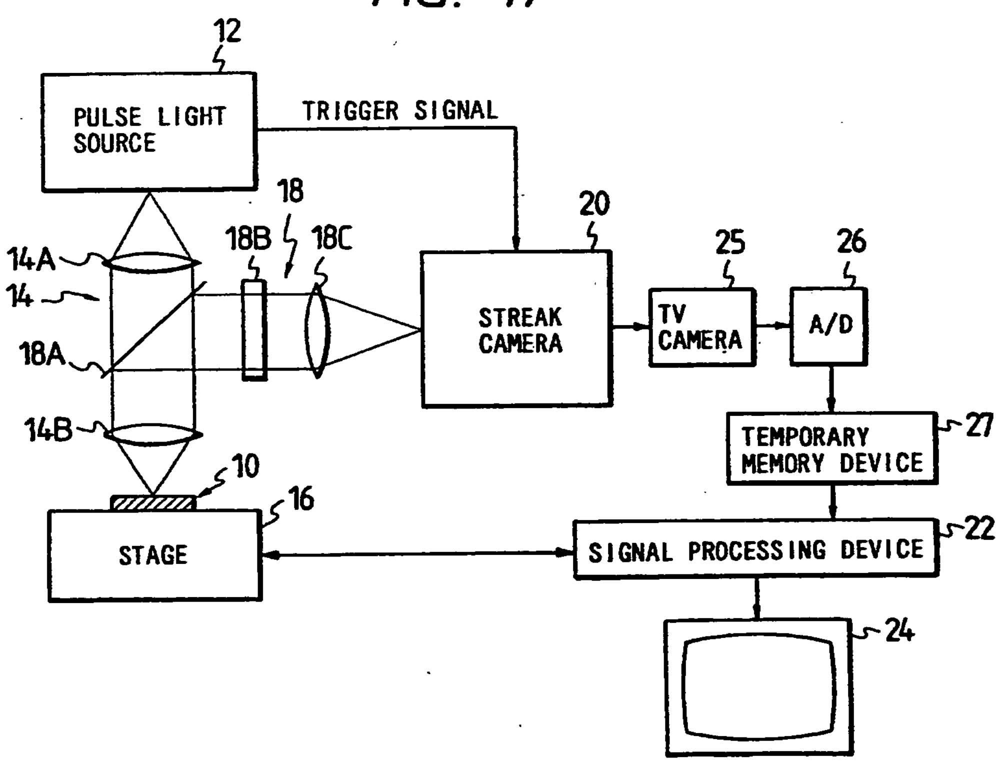

12
PULSE LIGHT SOURCE
TRIGGER SIGNAL
18
20
14A
18B
18C
25
26
14
18A
STREAK CAMERA
TV CAMERA
A/D
14B
TEMPORARY MEMORY DEVICE
27
10
16
STAGE
SIGNAL PROCESSING DEVICE
22
24

FIG. 18

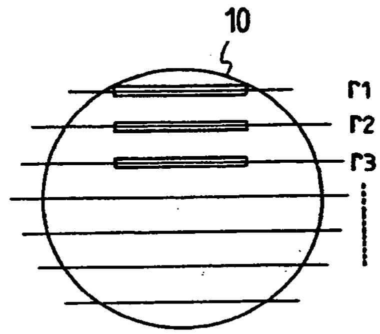
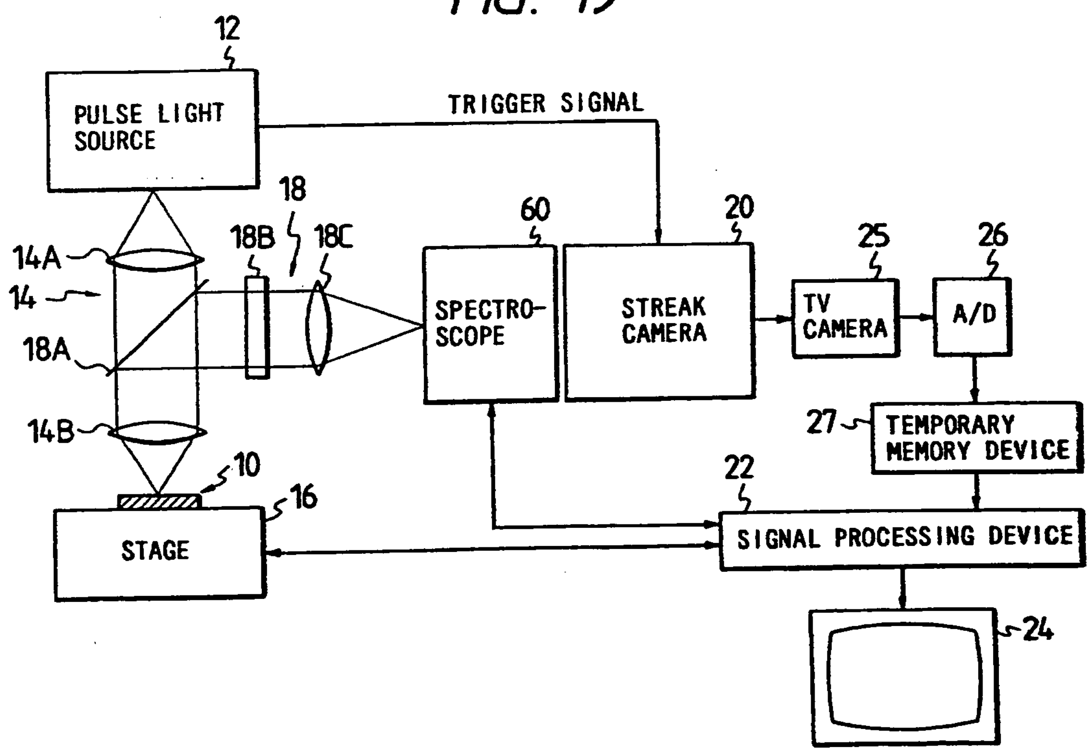

10
r1
r2
r3

FIG. 19


12
PULSE LIGHT SOURCE
TRIGGER SIGNAL
18
60
20
25
26
14A
14
18A
14B
18B
18C
SPECTRO-SCOPE
STREAK CAMERA
TV CAMERA
A/D
27
TEMPORARY MEMORY DEVICE
10
16
STAGE
22
SIGNAL PROCESSING DEVICE
24

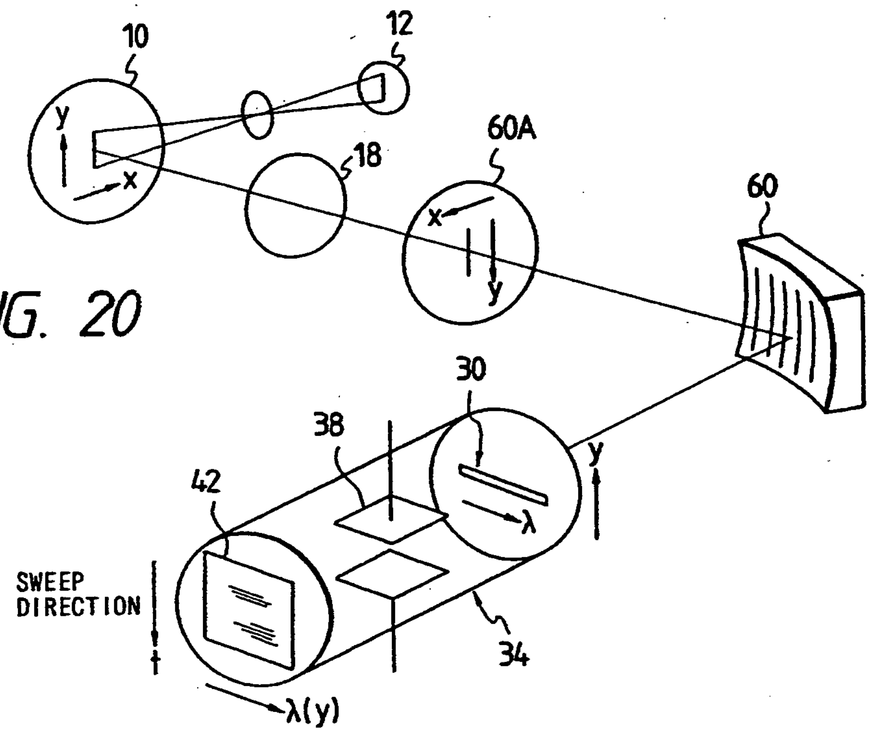

10
12
60A
18
60
30
38
42
SWEEP
DIRECTION
34
λ(y)
t
y
x
λ

FIG. 20

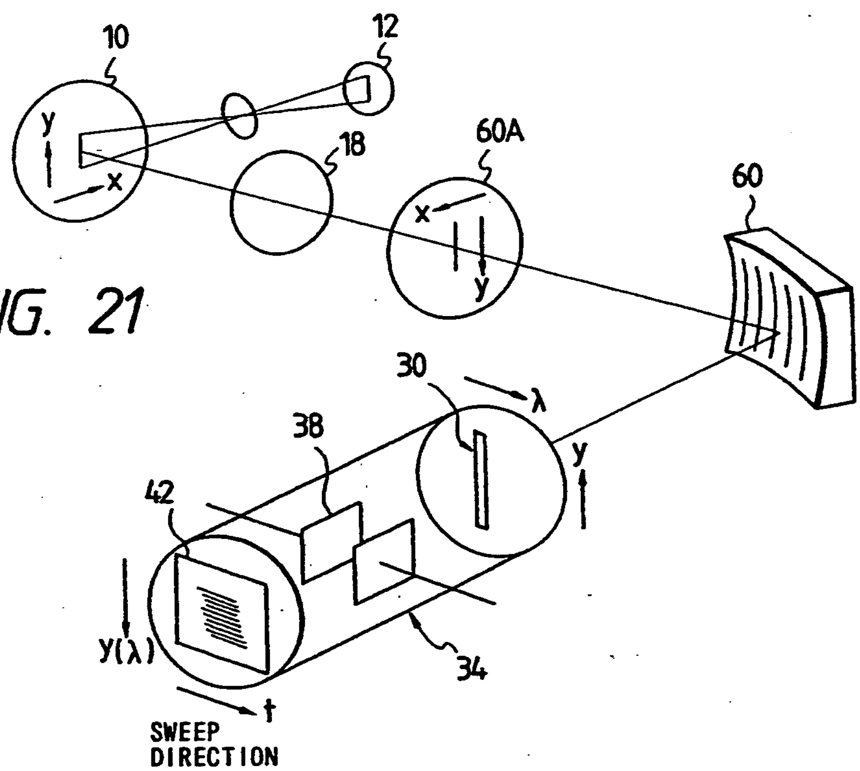

10
12
60A
18
60
30
38
42
34
y(λ)
t
SWEEP
DIRECTION
λ
y
x

FIG. 21

FIG. 22

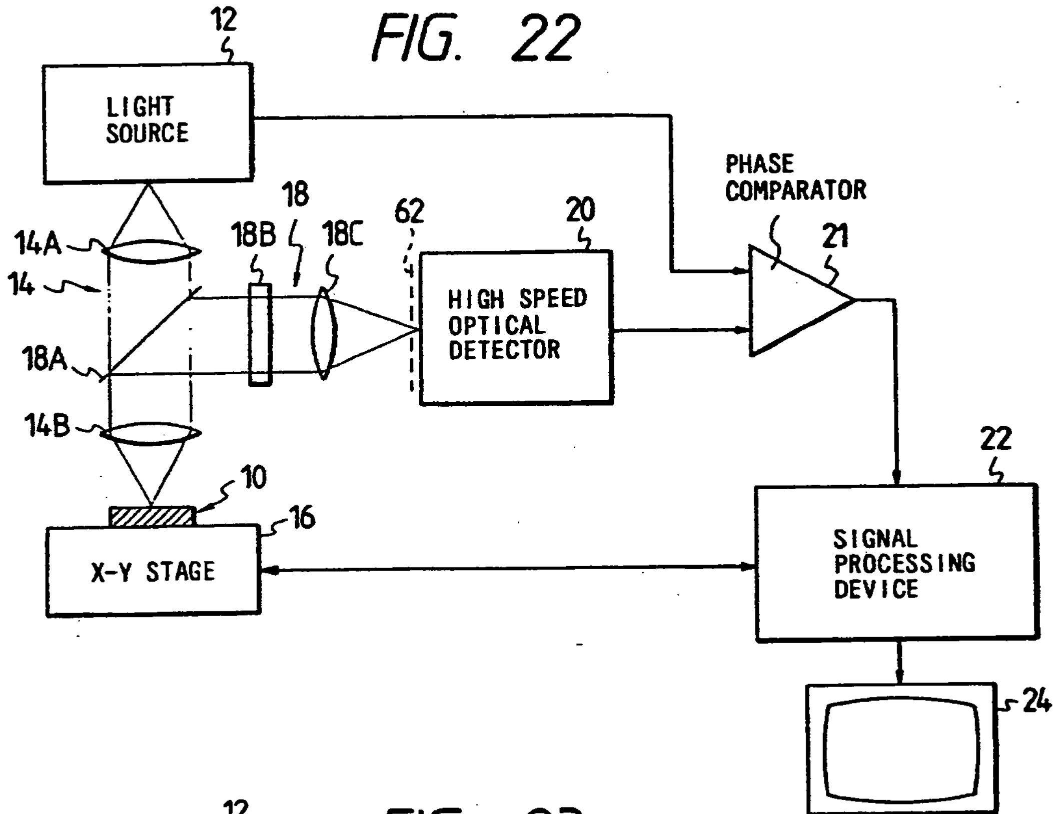

12
LIGHT SOURCE
14A
14
18A
14B
18
18B
18C
62
20
HIGH SPEED OPTICAL DETECTOR
PHASE COMPARATOR
21
10
16
X-Y STAGE
22
SIGNAL PROCESSING DEVICE
24

FIG. 23

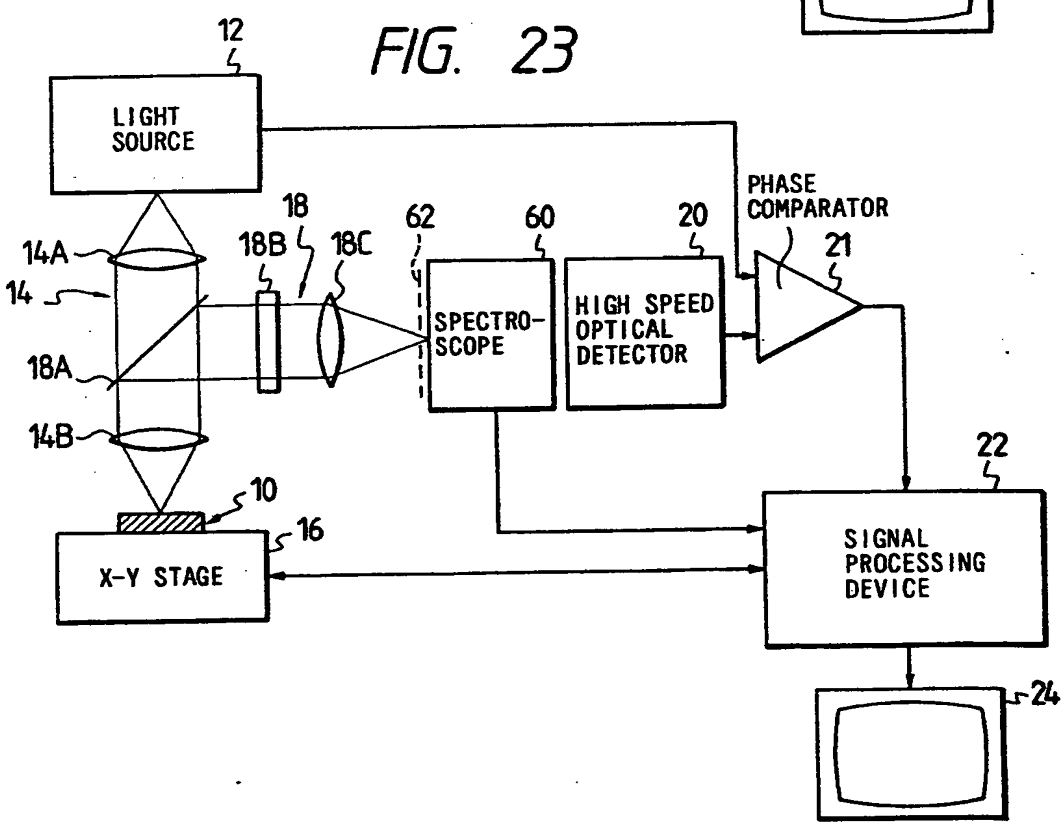
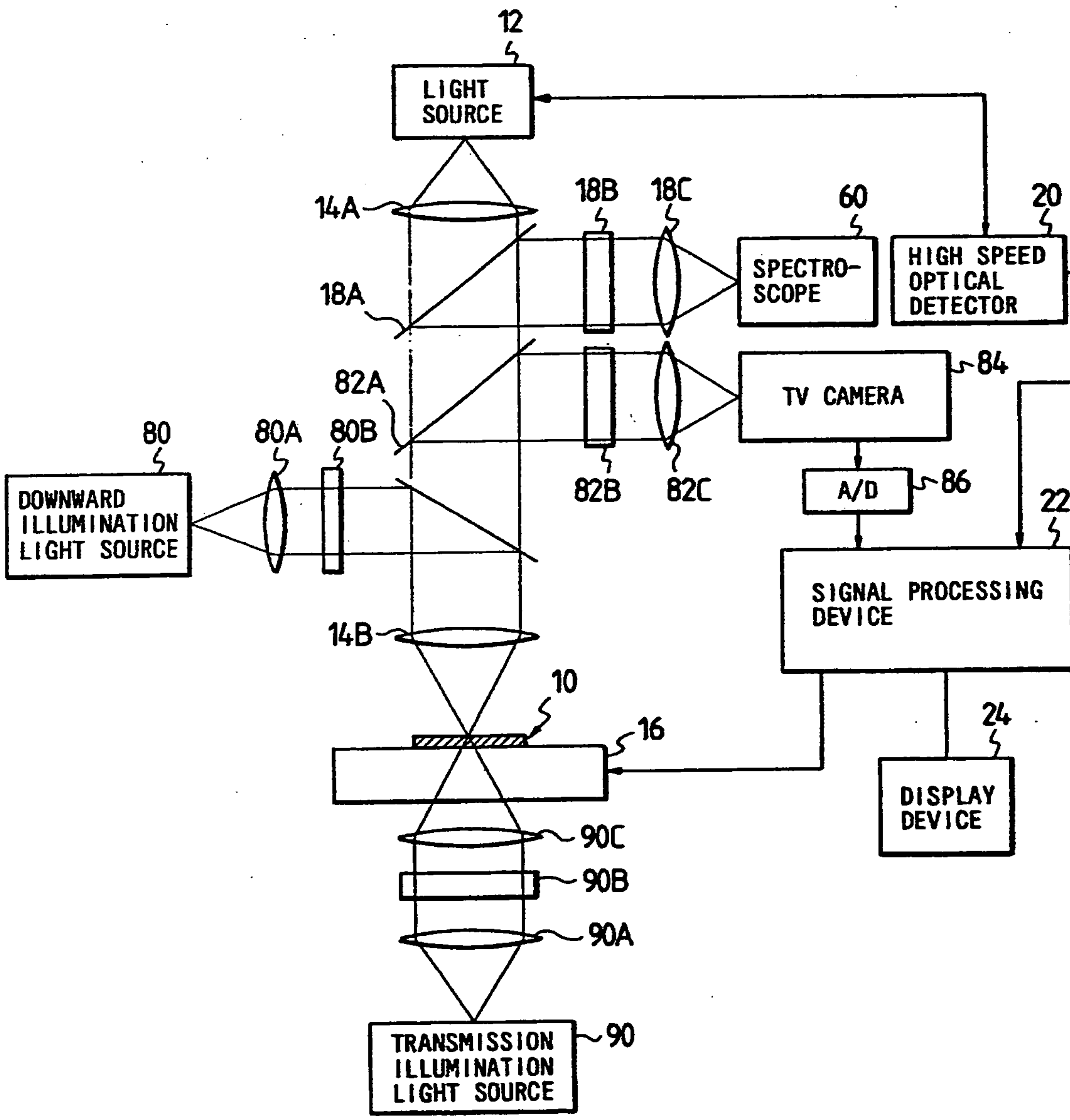

12
LIGHT SOURCE
14A
14
18A
14B
18
18B
18C
62
60
SPECTRO-SCOPE
20
HIGH SPEED OPTICAL DETECTOR
PHASE COMPARATOR
21
10
16
X-Y STAGE
22
SIGNAL PROCESSING DEVICE
24

FIG. 24


12
LIGHT SOURCE
14A
18B
18C
60
SPECTRO-SCOPE
20
HIGH SPEED OPTICAL DETECTOR
18A
82A
TV CAMERA
84
80
80A
80B
82B
82C
A/D
86
DOWNWARD ILLUMINATION LIGHT SOURCE
22
SIGNAL PROCESSING DEVICE
14B
10
16
24
DISPLAY DEVICE
90C
90B
90A
TRANSMISSION ILLUMINATION LIGHT SOURCE
90

FLUORESCENT CHARACTERISTIC INSPECTING APPARATUS

BACKGROUND OF THE INVENTION

The present invention relates to an apparatus for inspecting the fluorescent characteristics of a specimen, and more particularly to a fluorescent characteristic inspecting apparatus which can obtain the spatial intensity distribution image and lifetime distribution image of photoluminescence emitted from a specimen, being suitable for evaluation of a semiconductor wafer such as a GaAs wafer which is used for a light emitting diode (LED), laser diode (LD), field effect transistor (FET), photo-diode (PD), opto-electrical integrated circuit element (OEIC) and integrated circuit element (IC).

In manufacture of LEDs, LDs, FETs, PDs, OEICs, ICs, etc., the quality of GaAs wafers is one of the most important manufacturing conditions for the manufacturer, but it is not satisfactory enough yet.

In general, when a light beam having the energy higher than a forbidden band is applied to a semiconductor crystal to excite electrons from the valence band, fluorescence is observed during a period in which the electrons thus excited are recombined to lose the energy. The light emission is called photoluminescence. In the photoluminescence, the fluorescent lifetime depends on the quality, surface treatment, surface distortion, and scratches

of the crystal. Therefore, with the manufacturing steps such as polishing and etching, sometimes the surface recombination center decreases, and the fluorescent lifetime increases. This corresponds to the observation of the surface recombination rate. In general, the fluorescent lifetime is affected by the quality, defect, surface condition and surface treatment of the crystal. More specifically, a semiconductor wafer excellent in quality has a long fluorescent lifetime as indicated by the solid line A in Fig. 16; whereas a semiconductor wafer low in quality has a short fluorescent lifetime as indicated by the solid line B in Fig. 16. Hence, in evaluation of the quality of a GaAs wafer, it is essential to measure the fluorescent lifetime thereof.

In evaluation of the quality of a GaAs wafer, not only the fluorescent lifetime but also the fluorescence efficiency (quantum efficiency, fluorescence absolute value, or fluorescent intensity) is essential. In general, the fluorescent efficiency and the fluorescent lifetime correlate to each other as indicated in Fig. 16; however, sometimes not. Therefore, it is also important to measure the fluorescent intensity.

In a conventional apparatus for determining the quality of such a crystal by using the photoluminescence, a continuous light beam (DC light beam) having wavelength λ_1 is applied to a specimen to cause the latter to emit the

photoluminescence having wavelength λ_2 (> λ_1), the distribution of the intensity of which is used for evaluation of the specimen.

A technique has been proposed in the art, in which the output pulse beam of a mode locked synchronous pulse laser or semiconductor laser is applied to a specimen to produce the photoluminescence, and the fluorescent lifetime of the photoluminescence is measured by a sampling type streak camera.

However, in the prior art, the result of measurement is for only one measurement point, and therefore it is difficult to detect local defects.

SUMMARY OF THE INVENTION

Accordingly, an object of this invention is to eliminate the above-described difficulties. More specifically, an object of the invention is to provide a fluorescent characteristic inspecting apparatus which can obtain the spatial distribution images of fluorescent intensity and fluorescent lifetime of the photoluminescence emitted from a specimen, or the spatial correlation distribution image of the both.

The foregoing object of the present invention has been achieved by the provision of a fluorescent characteristic inspecting apparatus which comprises: a light source for exciting a specimen; a light applying optical

system for applying the output light of the light source to the specimen; moving means for moving the measurement position of the specimen; a light gathering optical system for applying the photoluminescence emitted from the specimen to a detector; a high speed optical detector for detecting data on the time intensity waveform of the photoluminescence in synchronization with the operation of the light source; and a signal processing device for analyzing and processing the data on the time intensity waveform at measurement points which are detected while the specimen measurement position is being moved, to obtain the spatial intensity distribution and lifetime distribution of the photoluminescence or the correlation distribution thereof.

In the fluorescent characteristic inspecting apparatus of the present invention, the fluorescent intensity and lifetime of the specimen, or the correlation thereof can be measured at high rate, and the quality of a GaAs wafer or the like can be evaluated with high accuracy. Furthermore, the spatial distribution images of fluorescent intensity and lifetime and the spatial distribution image of correlation thereof can be obtained, and therefore local defects can be readily detected.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is an explanatory diagram, partly as a block diagram, showing the arrangement of a first embodiment of a fluorescent characteristic inspecting apparatus according to the present invention,

Fig. 2 is a plan view showing one example of measurement points on the surface of a specimen in the present invention,

Fig. 3 is a sectional view showing the fundamental arrangement of a streak camera which is one example of a high speed optical detector employed in the present invention,

Fig. 4 is a block diagram showing one example of a signal processing system in the case where a streak camera is used as the high speed optical detector,

Fig. 5 is a diagram showing one example of the waveforms of exciting light and fluorescence,

Fig. 6 is a sectional view showing the fundamental arrangement of a sampling type streak camera which is another example of the high speed optical detector employed in the present invention,

Fig. 7 is a block diagram showing one example of a signal processing system in the case where the sampling type streak camera is employed as the high speed optical detector,

Fig. 8 is a block diagram for a description of the operating principle of a time correlation photon counter

which is another example of the high speed optical detector employed in the present invention,

Fig. 9 is a diagram showing one example of a fluorescent waveform which is provided by the time correlation photon counter,

Fig. 10 is a block diagram showing one modification of the time correlation photon counter,

Figs. 11 and 12 are graphical representations for a description of fluorescent lifetime determining methods,

Fig. 13 is a plan view showing one example of the display of the spatial distribution of fluorescent lifetime,

Fig. 14 is a block diagram showing a second embodiment of a fluorescent characteristic inspecting apparatus according to the present invention,

Fig. 15 is a diagram showing one example of the dependability of fluorescent lifetime on wavelengths, which can be measured by the apparatus according to the present invention,

Fig. 16 is a graphical representation indicating an example of the relation between semiconductor wafer quality and fluorescent waveform,

Fig. 17 is a block diagram showing the arrangement of a third embodiment of a fluorescent characteristic inspecting apparatus according to the present invention,

Fig. 18 is a plan view showing one example of measurement points on the surface of a specimen in the third embodiment of the apparatus according to the present invention,

Fig. 19 is a block diagram showing the arrangement of a fourth embodiment of an apparatus according to the present invention,

Fig. 20 is a perspective view showing the arrangement of essential components of the fourth embodiment,

Fig. 21 is a perspective view showing the arrangement of essential components of a fifth embodiment of a fluorescent characteristic inspecting apparatus according to the present invention,

Fig. 22 is a block diagram showing the arrangement of a sixth embodiment of a fluorescent characteristic inspecting apparatus according to the present invention,

Fig. 23 is a block diagram showing the arrangement of a seventh embodiment of the apparatus according to the present invention, and

Fig. 24 is a block diagram showing the arrangement of a eighth embodiment of an apparatus according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of a fluorescent characteristic inspecting apparatus according to the present invention,

which is applied to a semiconductor wafer evaluating device, will be described with reference to the accompanying drawings. The same or the like parts are designated by the same reference numerals throughout the drawings.

A first embodiment of the apparatus according to the present invention, as shown in Fig. 1, comprises: a pulse light source 12 for exciting a specimen 10 such as a GaAs semiconductor wafer; a light applying optical system 14 for applying the output light beam of the pulse light source 12 to the specimen 10; an X-Y stage 16 for two-dimensionally moving the position of the specimen 10 with respect to the pulse light source 12, thereby to move the measurement position (pulse light irradiation position) of the specimen two-dimensionally; a light gathering optical system 18 for extracting photoluminescence emitted from the specimen and applying it to a detector, including a beam splitter 18A, a filter 18B for extracting a wavelength component of the photoluminescence, and a lens 18C; a high speed optical detector 20 for obtaining data on the time intensity waveform of the photoluminescence (hereinafter referred to as "a fluorescence waveform"), with the output of the pulse light source 12 as a trigger signal; a signal processing device 22 for analyzing and processing the data on the fluorescent waveform at measurement points arranged, for example, in a matrix form (see Fig. 2), which are detected by moving the

X-Y stage 16 thereby to move the measurement position of the specimen, thereby to obtain the spatial intensity distribution and lifetime distribution of the photoluminescence; and a display device 24 for displaying the spatial intensity distribution image and lifetime distribution image provided by the signal processing device 22 and the correlation distribution image thereof.

The pulse light source 12 may be a laser diode (LD) which can stably output a pulse light beam having a wavelength of the order of 600 to 680 nm and a pulse width of the order of 30 psec. In measurement of relatively slow fluorescence less than several nanoseconds, a light emitting diode (LED) may be employed as the pulse light source.

The trigger signal can be obtained from the pulse light source 12 for instance as follows: The output pulse light of the pulse light source 12 is split into two parts, and one of the two parts is converted into an electrical signal with a high speed photo-diode such as an avalanche photo-diode (APD). The electrical signal is used as the trigger signal.

The high speed optical detector 20 may be a streak camera for instance.

The streak camera is an optical detector having a considerably high time resolution of several pico-seconds, thus being suitable for evaluation of a specimen such as a

GaAs wafer whose fluorescent lifetime is short, several tens of pico-seconds. The fundamental arrangement of the streak camera is as shown in Fig. 3. In the streak camera, an incident light beam is applied through an input optical system comprising a slit board 30 and a lens 32 to the photo-cathode 36 of a streak tube 34, to form an electron beam. The electron beam is deflected at high speed while passing through deflecting electrodes 38, so that the variable intensity of the incident light beam is detected as the variation of luminance on a phosphor screen 42. In Fig. 3, reference numeral 40 designates a micro-channel plate (MPC) for multiplying photoelectrons immediately before the phosphor screen 42.

The image formed on the output phosphor screen 42 is called "streak image". The streak image is photographed with a television camera 25 using a vidicon or CCD as shown in Fig. 4, and the distribution of brightness of the output image in the direction of time axis is quantized, to detect the variation in intensity of the light beam under test. More specifically, the output of the television camera 25 is subjected to analog-to-digital (A/D) conversion by an A/D converter 26, the output of which is temporarily stored in a temporary memory device 27 and then applied to the above-described signal processing device 22. Instead of the

television camera 25, a one-dimensional photo-diode array may be used.

In the case where the streak camera is employed, a fluorescent waveform as shown in Fig. 5 is obtained at each of the measurement points, and the fluorescent intensities and lifetimes obtained from those fluorescent waveforms are two-dimensionally plotted in correspondence to the measurement points, to obtain the spatial intensity distribution image and lifetime distribution image.

The high speed optical detector 20 may be a sampling type streak camera as shown in Fig. 6. The sampling type streak camera can be obtained by modifying the above-described streak camera as follows: In the streak camera, a slit board 39 is disposed between the deflecting electrodes 38 and the phosphor screen 42 to spatially limit the streak image, so that the streak image is electrically sampled, and the images thus sampled are combined when necessary.

In this case, as shown in Fig. 7, the intensity of a luminescent spot sampled is detected by a photo-multiplier 28 or photo-diode, amplified by an amplifier 29 when necessary, and applied through an A/D converter 26 and a temporary memory device 27 to the above-described signal processing device 22.

The high speed optical detector 20 may be a time correlation photon counter. The time correlation photon counter, as shown in Fig. 8, comprises a photo-multiplier (PMT) 50 for detecting the photoluminescence of one photon level emitted from a specimen 10; a time-amplitude converter (TAC) 52 which starts a counting operation in response to the trigger signal from the pulse light source 12, and suspends the counting operation upon detection of a photon by the PMT 50, so as to output a voltage pulse whose height is proportional to the time interval between two pulse signals; and a pulse height analyzer (PHA) 54 for quantizing the height of the output pulse of the TAC 52 to store it.

The quantity of light incident to the PMT 50 is adjusted by controlling the pulse light intensity or providing a filter before the PMT 50 to the extent that at most one photoelectron is detected per pulse light application.

The PHA (pulse height analyzer) 54 stores the heights of pulses applied thereto and the numbers of times of application of each pulse. Therefore, after the light source has emitted several thousands of light pulses, the content of the PHA 54 is as shown in Fig. 9. In Fig. 9, the horizontal axis represents the time interval from the light emission of the light source till the detection of one photon of the fluorescence, while the vertical axis represents the

probability of detecting a photon at a time instant; i.e., the fluorescent intensity at that time instant. Thus, Fig. 9 shows a fluorescent waveform.

In the case where the time correlation photon counter is employed, one photon which is the minimum unit of light is detected, and therefore the detection can be achieved with high accuracy. In addition, the time resolution is high, and the dynamic range is wide.

The intensity distribution of the photoluminescence can be obtained by integration of the value I(t) of the waveform within a predetermined period of time. In order to obtain only the intensity distribution quickly or with high S/N ratio, as shown in Fig. 10, the output pulse signal of the PMT (photomultiplier) 50 is counted with a high speed pulse counter 56 provided additionally, and the signal processing circuit 22 is operated to obtain an intensity distribution image. In this case, time data is not required, and therefore the pulse source 12 may be operated in a direct current (DC) mode, and the counting rate may be increased to the maximum count rate of the PMT, amplifier or pulse counter. Thus, prior to the measurement of the fluorescent lifetime distribution for instance, the intensity distribution image is obtained quickly, and the range of measurement of the fluorescent lifetime distribution can be determined from the image thus obtained. In a general time

correlation counting method, the system counting rate is limited mainly by the maximum counting rate of the TAC (time-amplitude converter) (normally several hundreds of k cps (kilo cycles per second)). In a photon counting method shown in Fig. 10, the counting rate may be around 100 M cps (mega cycles per second), and therefore the measurement time can be greatly reduced.

The high speed optical detector 20 may be made up of a high speed photo-diode such as an avalanche photo-diode (APD) and a waveform memory.

In the signal processing device 22, the data on the fluorescent waveform is analyzed and processed as follows:

According to a fluorescent waveform as shown in Fig. 5, first the time required for the fluorescent intensity I(t) to reach 1/e (about 37%); i.e., a fluorescent lifetime τ is obtained. More specifically, in the case where there is only one kind of fluorescent lifetime τ, the above-described fluorescent waveform is as shown in Fig. 11 in which the vertical axis is of logarithmic scale. The following equation(1) is applied to the waveform, so that the nearest parameter term A and the lifetime τ are obtained, for instance, by the least square method:

$$I(t) = A \exp(- t/\tau) \text{ ------------- } (1)$$

In the case where there are a plurality of fluorescent lifetimes (τ_1, τ_2, ...), the fluorescent

waveform is as shown in Fig. 12 in which the vertical axis is of logarithmic scale. By applying the following equation(2) to the waveform, the fluorescent lifetimes τ_1, τ_2,.... can be obtained:

$$I(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2) + A_3 \exp(-t/\tau_3) + \ldots\ldots \quad \text{------------------} \ (2)$$

On the other hand, the (total) intensity of the fluorescence corresponds to the total area (shaded in Fig. 11 or 12) of the waveform. Therefore, the intensity can be obtained by integrating the value I(t) of the waveform over the entire range, or it can be calculated according to the following equation(3) using constant A_i and fluorescent lifetime τ_i which have been obtained before:

$$\int I(t) = A_1\tau_1 + A_2\tau_2 + A_3\tau_3 + \ldots\ldots\ldots \quad \text{---------------} \ (3)$$

The fluorescent lifetime and fluorescent intensity thus obtained are displayed as a spatial distribution image on the display device 24. One example of the fluorescent lifetime image thus displayed is as shown in Fig. 13. In Fig. 13, the fluorescent lifetime distribution is indicated by gradation.

The photoluminescence intensity and lifetime may be displayed as a monochromatic image using a plurality of

densities, or as a color image using various colors, or may be displayed three-dimensionally. In the case where the fluorescent lifetime includes the secondary component τ_2 and the tertiary component τ_3, the following methods may be employed: The primary component τ_1 is mapped in green, the primary and secondary components τ_1 and τ_2 are mapped in red, and the primary, secondary and tertiary components τ_1, τ_2 and τ_3 are mapped in yellow. Alternatively, the primary component τ_1 is indicated in red, the secondary component τ_2 in green, and the tertiary component τ_3 in blue; that is, those colors are overlapped so that the primary component τ_1, the secondary component τ_2 and the tertiary component τ_3 are indicated in red, yellow and white, respectively. Furthermore, the image may be processed by smoothing so that it can be read with ease.

The signal processing device 22 can operate to obtain the correlation (such as ratio) of different intensity distribution images and lifetime images, and to display the result of operation (the correlation distribution image).

A second embodiment of a fluorescent characteristic inspecting apparatus according to the present invention will be described with reference to Fig. 14 in detail.

The second embodiment is a semiconductor wafer evaluating apparatus which comprises a pulse light source 12, a light applying optical system 14, an X-Y stage 16, a light

gathering optical system 18, a high speed optical detector 20, a signal processing device 22 and a display device 24 which are the same as those in the first embodiment described above, and which further comprises a spectroscope 60 disposed immediately before the high speed optical detector 20 to form the spectrum of the photoluminescence of the specimen 10, so that a fluorescent waveform is detected for every wavelength to obtain a spatial intensity distribution image and lifetime distribution image for every wavelength.

With the second embodiment of the fluorescent characteristic inspecting apparatus of the present invention, wavelength data can also be measured at the same time. For instance in the case where, as shown in Fig. 15, different fluorescent lifetimes are provided for different wavelengths, the different fluorescent lifetimes τ_1 and τ_2 can be obtained with high accuracy.

If, in the second embodiment, a two-dimensional streak camera is employed as the high speed optical detector, then a fluorescent waveform including waveform data can be obtained immediately, which eliminates the wavelength scan at the spectroscope 60.

A third embodiment of an apparatus of the present invention will be described with reference to Fig. 17, in which a specimen is excited by a slit-shaped light beam or a plurality of light beams, and the data on the time intensity

waveform of photoluminescence of the specimen is detected two-dimensionally, whereby the spatial intensity distribution and lifetime distribution of the photoluminescence or the correlation distribution thereof is obtained. The arrangement of the third embodiment is almost the same as that of the first embodiment shown in Fig. 1. That is, as shown in Fig. 17, the third embodiment of the apparatus of the present invention comprises: a pulse light source 12 for outputting a slit-shaped light beam to excite a specimen 10 such as a GaAs semiconductor wafer; a light applying optical system 14 for applying the output light beam of the pulse light source 12 to the specimen 10; a stage for finely moving the position of the specimen with respect to the pulse light source 12 in a direction perpendicular to the longitudinal direction of the slit-shaped light beam and for coarsely in the longitudinal direction of the slit-shaped light beam, thereby to move the measurement position (pulse light beam applied position) of the specimen 10; a light gathering optical system 18 for extracting the photoluminescence emitted from the specimen 10 and applying it to a detector, including a beam splitter 18A, a filter 18B for extracting a waveform component of the photoluminescence, and a lens 18C; a streak camera 20 for two-dimensionally reading data on the time intensity waveform of the photoluminescence (hereinafter referred to as "a fluorescent waveform"); a signal processing

device 22 for analyzing and processing data on the fluorescent waveforms at a plurality of measurement points in the form of a plurality of parallel slits (see Fig. 18), which are detected in a parallel mode, while the stage 16 is being moved to move the specimen measurement position, thereby to obtain the spatial distributions of fluorescent intensity and lifetime of the photoluminescence, and the distribution of correlation thereof; and a display device 24 for displaying the spatial intensity distribution image and lifetime distribution image, and the correlation distribution image provided by the signal processing device 22.

The pulse light source 12 may be a laser diode (LD) which can stably oscillate a pulse light beam having a wavelength of the order of 600 to 680 nm and a pulse width of the order of 50 psec. A trigger signal can be obtained from the pulse light source 12 by the same way as in the first embodiment. The streak camera 20 is the same as shown in Fig. 3, and thus the description thereof will be omitted.

For each of the measurement points arranged in the form of parallel slits, a fluorescent waveform as shown in Fig. 5 is obtained with the streak camera 20. And the fluorescent intensities and lifetimes at the measurement points are detected from the fluorescent waveforms thus obtained, and plotted two-dimensionally in correspondence to the measurement points, whereby the spatial intensity

distribution image and lifetime distribution image can be obtained quickly.

In the above-described embodiment, the length of the slit-shaped light beam is coincided with the range of measurement, and normally it is unnecessary to move the specimen in the longitudinal direction of the slit-shaped light beam. However, the range of measurement can be increased by coarsely moving the stage in the longitudinal direction of the slit-shaped light beam and in a direction perpendicular to the longitudinal direction.

The signal processing device 22 analyzes and processes the data on the fluorescent waveform in the same way as in the first embodiment, and the similar results are obtained. Thus the description thereof will be omitted.

A fourth embodiment of a fluorescent characteristic inspecting apparatus according to the present invention will be described with reference to Fig. 19 in detail.

The fourth embodiment is a semiconductor wafer evaluating apparatus which comprises: a pulse light source 12 or spot light source 12; a light applying optical system 14; a stage 16; a light gathering optical system 18; a streak camera 20, a signal processing device 22; a display device 24; a television camera 50; an A/D converter 52; and a temporary memory device 52 which are all similar to those in the above-described third embodiment of the apparatus of the

present invention (Fig. 17). The semiconductor wafer evaluating apparatus further comprises: a spectroscope 60 disposed immediately before the streak camera 20 to form the spectrum of the photoluminescence of the specimen 10. As shown in Fig. 20, the streak camera 20 performs a sweep in a direction perpendicular to the spectral direction so that the spectroscopic analysis of the photoluminescence from the measurement point is carried out in a time resolution mode to obtain a spatial intensity distribution image and lifetime distribution image for each wavelength. In this case, one measurement point is selected for each measurement; however, the lifetimes for a number of wavelengths can be detected concurrently.

In Fig. 20, reference character 60A designates the incident slit of the spectroscope 60 which is arranged on the image-forming surface; 30, the incident slit of the streak camera 20; 38, the deflecting electrodes of the streak camera; and 42, the phosphor screen.

With the fourth embodiment of the apparatus according to the present invention, data on a number of wavelengths can be measured simultaneously. Therefore, even if, as shown in Fig. 15, different fluorescent lifetimes are provided for different wavelengths, the different fluorescent lifetimes τ_1 and τ_2 can be obtained with high accuracy.

In the above-described fourth embodiment, the fluorescent waveforms including waveform data can be obtained promptly, which eliminates the wavelength scan of the spectroscope 60.

A fifth embodiment of a fluorescent characteristic inspecting apparatus according to the present invention will be described in detail. The fifth embodiment is a semiconductor wafer evaluating apparatus similar to the fourth embodiment described above which is so modified that, as shown in Fig. 21, in the streak camera 20, a sweeping operation is carried out in the spectral direction so that, at each of the measurement points, spatial intensity distribution images and lifetime distribution images, or the correlation distribution images thereof are obtained in a parallel mode for each wavelength. The others are similar to those in the above-described fourth embodiment.

The streak camera 20 may be rotated by 90 degrees, so that the operations in the fourth and fifth embodiments can be changed to each other.

A sixth embodiment will then be described with reference to Fig. 22, in which the spatial intensity distribution image and lifetime distribution image of a photoluminescence emitted from a specimen or the correlation distribution thereof can be obtained by using an intensity-modulated light to excite the specimen. As shown in Fig. 22,

the sixth embodiment of the apparatus according to the present invention comprises: an intensity-modulated light source 12 for exciting a specimen 10 such as a GaAs semiconductor wafer; a light applying optical system 14 for applying the output light beam of the light source 12 to the specimen 10; an X-Y stage 16 for two-dimensionally moving the position of the specimen 10 with respect to the light source 12, thereby to move the measurement position (light irradiation position) of the specimen 10 two-dimensionally; a light gathering optical system for extracting the photoluminescence emitted from the specimen 10 and applying it to a detector, including a beam splitter 18A, a filter 18B for extracting a wavelength component of the photoluminescence, and a lens 18C; a high speed optical detector 20 for detecting the photoluminescence; a phase comparator 21 for obtaining the phase difference between the light beam of the light source 12 and the output signal of the high speed optical detector; a signal processing device 22 for analyzing and processing the phase differences at measurement points arranged in a matrix form for instance (see Fig. 2) while the X-Y stage 16 is moved to move the measurement position of the specimen, thereby to obtain the spatial distributions of fluorescent intensity and lifetime of the photoluminescence or the spatial distribution of correlation thereof; and a display device 24 for displaying

the spatial distribution images of fluorescent intensity and lifetime or the spatial distribution image of correlation thereof, which are provided by the signal processing device 22.

The light source 12 may be a laser diode (LD) or light emitting diode (LED) which can stably output an intensity-modulated light beam having a wavelength of the order of 600 to 680 nm. The light emission of the light source 12 may be detected for instance as follows: The output light beam of the light source 12 is split into two parts, and one of the two parts is converted into an electrical signal with a high speed photo-diode such as an avalanche photo-diode (APD).

The high speed optical detector 20 may be a high speed photo-diode or photomultiplier.

In the signal processing device 22, the data on the fluorescent waveform is analyzed and processed as follows:

The exciting light beam is modulated with a sine wave. That is, when the specimen 10 is excited with a sine wave $\ell(t)$ as defined by the following equation (4), the fluorescent waveform $f(t)$ becomes a sine wave whose phase is shifted by $\phi = \tan^{-1}(\omega\tau)$. The photoluminescence intensity can be obtained from the average power of the fluorescent waveform $f(t)$.

$$\ell(t) = L_1 \sin(\omega t) + L_0 \text{ ------------ } (4)$$

The fluorescent lifetime and fluorescent intensity thus obtained are displayed as a spatial distribution image on the display device 24 in the same way as in the foregoing embodiments. For example, the image of the fluorescent lifetime τ is displayed as shown in Fig. 13.

The signal processing device 22 can operate to obtain the correlation (such as ratio) of different intensity distribution images and lifetime images, and to display the result of operation (the correlation distribution image).

A seventh embodiment of a fluorescent characteristic inspecting apparatus according to the present invention will be described with reference to Fig. 23 in detail.

The seventh embodiment is a semiconductor wafer evaluating apparatus which comprises a light source 12, a light applying optical system 14, an X-Y stage 16, a light gathering optical system 18, a high speed optical detector 20, a phase comparator 21, a signal processing device 22 and a display device 24 which are the same as those in the sixth embodiment described above, and which further comprises a spectroscope 60 disposed immediately before the high speed optical detector 20 to form the spectrum of the photoluminescence of the specimen 10, so that a fluorescent waveform is detected for every wavelength to obtain a spatial intensity distribution image and lifetime distribution image for every wavelength.

With the seventh embodiment of the fluorescent characteristic inspecting apparatus, wavelength data can also be measured at the same time. For instance in the case where, as shown in Fig. 15, different fluorescent lifetimes are provided for different wavelengths, the different fluorescent lifetimes τ_1 and τ_2 can be obtained with high accuracy.

In the above-described embodiments of the apparatus according to the present invention, the X-Y stage 16 is used to move the measurement position of the specimen 10; however, it should be noted that means for moving measurement position is not limited thereto or thereby. For instance, in the case where a belt conveyor is used to move the specimen 10, the means may be designed to move the light source 12 one-dimensionally in a direction perpendicular to the direction of conveyance of the belt conveyor. Furthermore, instead of the mechanical scanning means, the means may be constructed such that the light beam is electrically deflected in a scanning mode, or this light beam deflecting operation is combined with movement of the specimen.

In addition, an aperture 62 may be provided before the input image forming surface of the high speed optical detector 20 or spectroscope 60 as indicated at the broken line in Fig. 1, 14, 22 or 23 to form a confocal system. In this case, data can be obtained for every focusing point, so

that resolution can be obtained not only in the scanning direction (two-dimensional direction) but also in the direction of depth of the specimen.

Fig. 24 shows an eighth embodiment of a fluorescent characteristic inspecting apparatus according to the present invention. In this embodiment, in addition to the above-described light source 12, a downward illumination light source 80 is provided to apply light through a lens 80A to the specimen 10. The light reflected from the specimen 10 is applied to a TV camera 84 through a mirror 82A and a lens 82C, as a result of which the TV camera 84 provides a reflection image. The output of the TV camera 84 is subjected to analog-to-digital (A/D) conversion by an A/D converter 86, the output of which is applied through a signal processing device 22 to an image memory (not shown), where it is stored. The contents of the image memory are displayed on a display device 24, so that the position of the light on the specimen 10 can be confirmed and the condition of the region under measurement can be monitored.

The reflection image and the photoluminescence lifetime distribution image or intensity distribution image can be displayed in combination.

The downward illumination light source 80 may be provided with a wavelength filter 80B in correspondence to the absorption wavelength of the specimen 10. In this case,

the entire surface of the specimen 10 is irradiated to produce a photoluminescence image which is applied through a predetermined wavelength filter 82B to the TV camera 84, so as to obtain a two-dimensional photoluminescence intensity distribution.

Further, a transmission illumination light source 90, lenses 90A and 90C and a wavelength filter 90B may be provided on the side of the rear surface of the specimen 10, so that the image of the specimen formed by light passed therethrough is detected by the TV camera 84 or high speed optical detector 20 so as to be compared with the photoluminescence lifetime and intensity distribution images. In this case, the second harmonic wave component attributed to the non-linearity of the specimen is extracted with spectroscopic means provided before the high speed optical detector 20, so that a non-linear optical characteristic image is obtained by scanning the specimen 10.

In the above-described embodiments, the technical concept of the invention is applied to the semiconductor wafer evaluating apparatus for inspecting semiconductor wafer; however, the invention is not limited thereto or thereby. That is, the technical concept of the invention can be equally applied to apparatuses for inspecting other fluorescent characteristics of dielectric substances, fluorescent surfaces, chemical agents, paper, organism, etc.

CLAIMS

1. A fluorescent characteristic inspecting apparatus, comprising:

a light source for exciting a specimen;

a light applying optical system for applying output light of said light source to said specimen;

moving means for moving a measurement position of said specimen;

a light gathering optical system for extracting photoluminescence emitted from said specimen and applying it to a detector;

a high speed optical detector for detecting data on a time intensity waveform of said photoluminescence in synchronization with the operation of said light source; and

a signal processing device for analyzing and processing said data on said time intensity waveform at measurement points, which are detected while said measurement position is being moved, to obtain the spatial intensity distribution and lifetime distribution of said photoluminescence or the correlation distribution of the both.

2. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said high speed optical detector is a streak camera.

3. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said high speed optical detector is a time correlation photon counter.

4. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said high speed optical detector is a high speed photodiode.

5. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said moving means operates to mechanically move said specimen.

6. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said moving means operates to deflect the output light beam of said light source in a scanning mode.

7. A fluorescent characteristic inspecting apparatus as claimed in claim 1, wherein said moving means operates to mechanically move said specimen and to deflect the output light beam of said light source in a scanning mode.

8. A fluorescent characteristic inspecting apparatus as claimed in claim 1, further comprising spectroscopic means provided immediately before said high speed optical detector, to obtain a spatial intensity distribution and lifetime distribution for each wavelength.

9. A fluorescent characteristic inspecting apparatus as claimed in claim 1 or 8, wherein said light gathering optical system is a confocal optical system, and an aperture is

provided before an input image-forming surface of said high speed optical detector or spectroscopic means, to have resolution in the direction of depth of said specimen.

10. A fluorescent characteristic inspecting apparatus as claimed in claim 2, wherein said light source emits a slit-shaped light beam or a plurality of light beams to excite said specimen, so that said data on the time intensity waveform of said photoluminescence of said specimen is two-dimensionally detected.

11. A fluorescent characteristic inspecting apparatus as claimed in claim 10, further comprising spectroscopic means provided before said streak camera, wherein, with a sweeping operation in a direction perpendicular to a spectral direction, the spectroscopic analysis of said photoluminescence from said measurement point is performed in time resolution mode, to obtain in a parallel mode spatial intensity distributions and lifetime distributions or correlation distributions thereof for a number of wavelengths.

12. A fluorescent characteristic inspecting apparatus as claimed in claim 10, further comprising spectroscopic means which can be scanned and is provided before said streak camera, wherein a sweep operation is carried out in a spectral direction to obtain in a parallel mode spatial intensity distributions and lifetime distributions or

correlation distributions thereof for each of predetermined wavelengths of said photoluminescence at a plurality of measurement points.

13. A fluorescent characteristic inspecting apparatus as claimed in claim 10, further comprising spectroscopic means provided before said streak camera, wherein said streak camera can be rotated by 90 degrees, so that, with a sweeping operation in a direction perpendicular to a spectral direction, the spectroscopic analysis of said photoluminescence from said measurement point is performed in time resolution mode to obtain in a parallel mode spatial intensity distributions and lifetime distributions or correlation distributions thereof for a number of wavelengths, or a sweeping operation is carried out in a spectral direction to obtain in a parallel mode spatial intensity distributions and lifetime distributions or correlation distributions thereof for each of predetermined wavelengths of said photoluminescence at a plurality of measurement points.

14. A fluorescent characteristic inspecting apparatus as claimed in claim 10, 11, 12, or 13, wherein said streak camera includes a streak tube which has a slit-shaped photocathode or accelerating electrode.

15. A fluorescent characteristic inspecting apparatus as claimed in claim 1, further comprising a phase comparator,

wherein said light source outputs an intensity-modulated light, said phase comparator calculates a phase difference between said output light beam of said light source and an output signal of said high speed optical detector, and said signal processing device analyzes and processes the phase differences at measurements points to obtain the spatial distributions of intensity and lifetime of said photoluminescence or the spatial distribution of correlation thereof through a phase difference method.

Published 1990 at The Patent Office, State House, 66/71 High Holborn, London WC1R 4TP. Further copies may be obtained from The Patent Office. Sales Branch, St Mary Cray, Orpington, Kent BR5 3RD. Printed by Multiplex techniques ltd, St Mary Cray, Kent, Con. 1/87